Theoretical developments in the SMEFT beyond dimension-6

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Snowmass Community Summer Study

July 22, 2022

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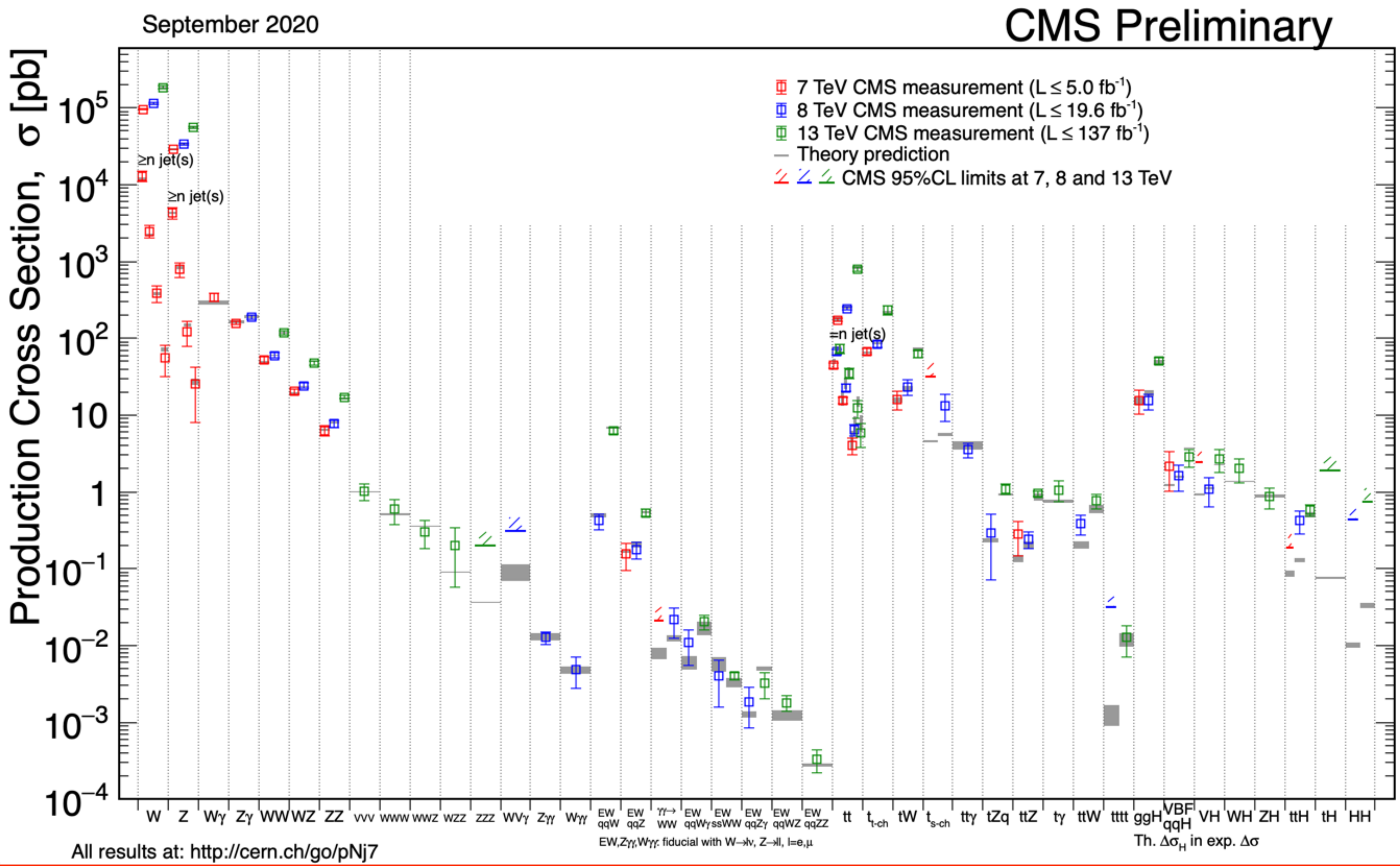
Outline

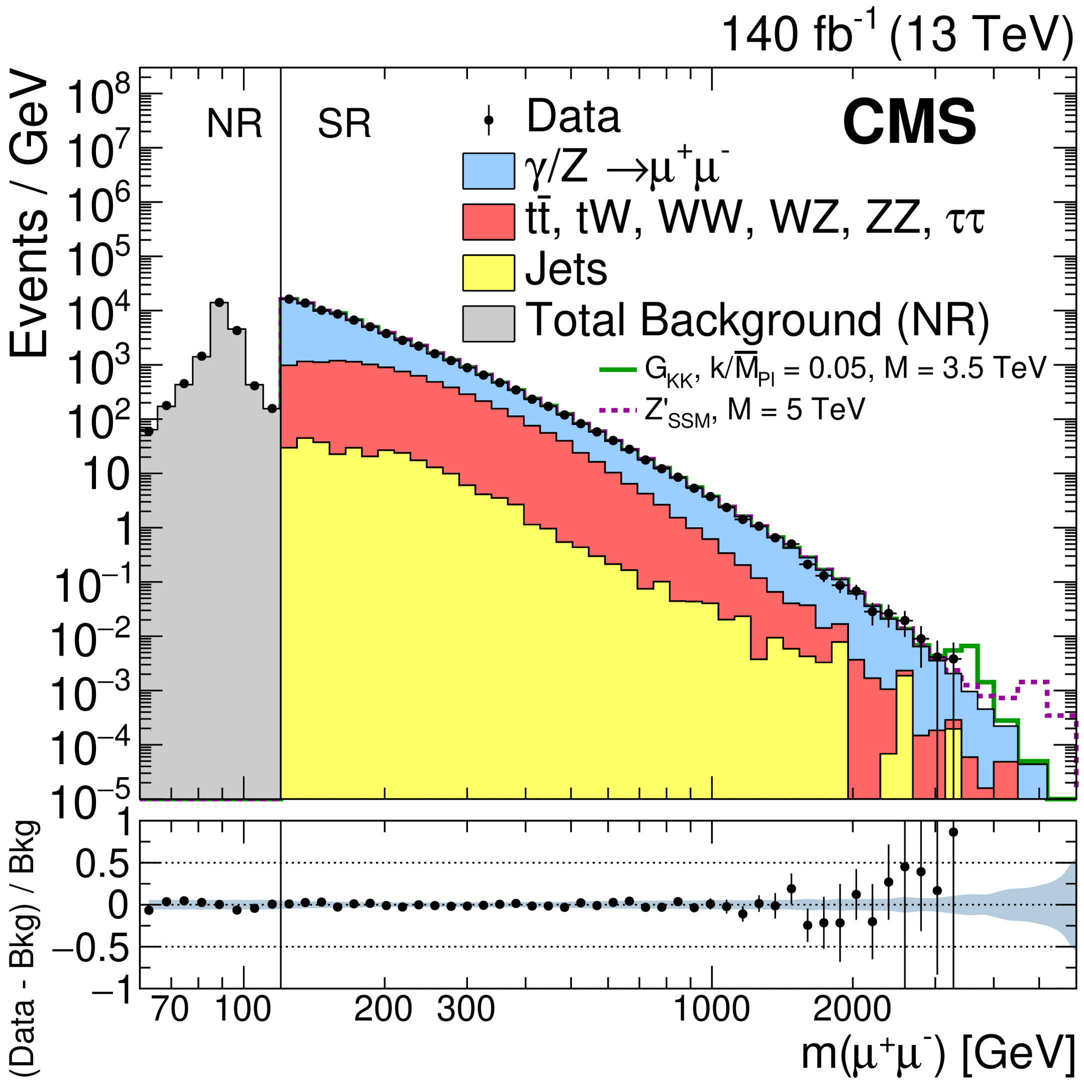
- Counting of operators beyond dimension-6 and construction of the explicit operator basis
- RGE running at dimension-8, and its interplay with positivity bounds on Wilson coefficients
- Phenomenology at dimension-8: opportunities with LHC data, synergies with other experiments, and dimension-8 as a diagnostic tool
- The focus will be on new results obtained during the past two years while the Snowmass process was taking place.

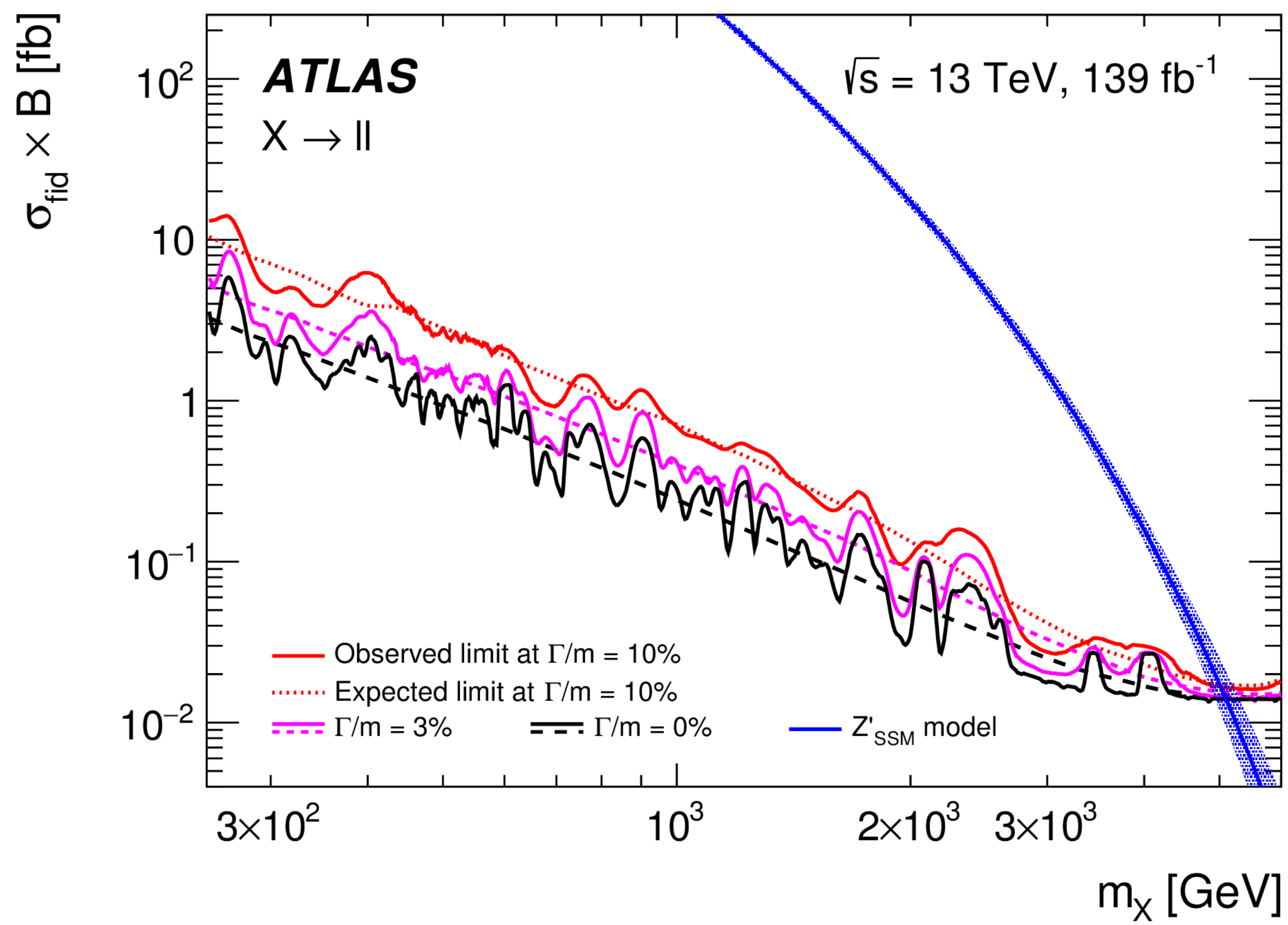
Status of the SM



Remarkable agreement between SM theory and experiment over dozens of processes and orders of magnitude in cross section. No BSM states found so far!

Resonance searches





Sensitivity to new resonances has reached 5 TeV in some models. Suggests a mass gap between SM and new physics; indirect searches increasingly important

Framework for future searches

- Two approaches for future indirect searches:
  - Formulate specific BSM models, calculate predictions for the LHC and other experiments
  - Adopt an EFT framework that encapsulates a broad swath of possible BSM theories

- Standard Model Effective Field Theory (SMEFT): all operators consistent with SM symmetries, containing SM particles, and assuming a mass gap to any new physics

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_{6,i}\mathcal{O}_{6,i} + \frac{1}{\Lambda^4}\sum_i C_{8,i}\mathcal{O}_{8,i}}$$

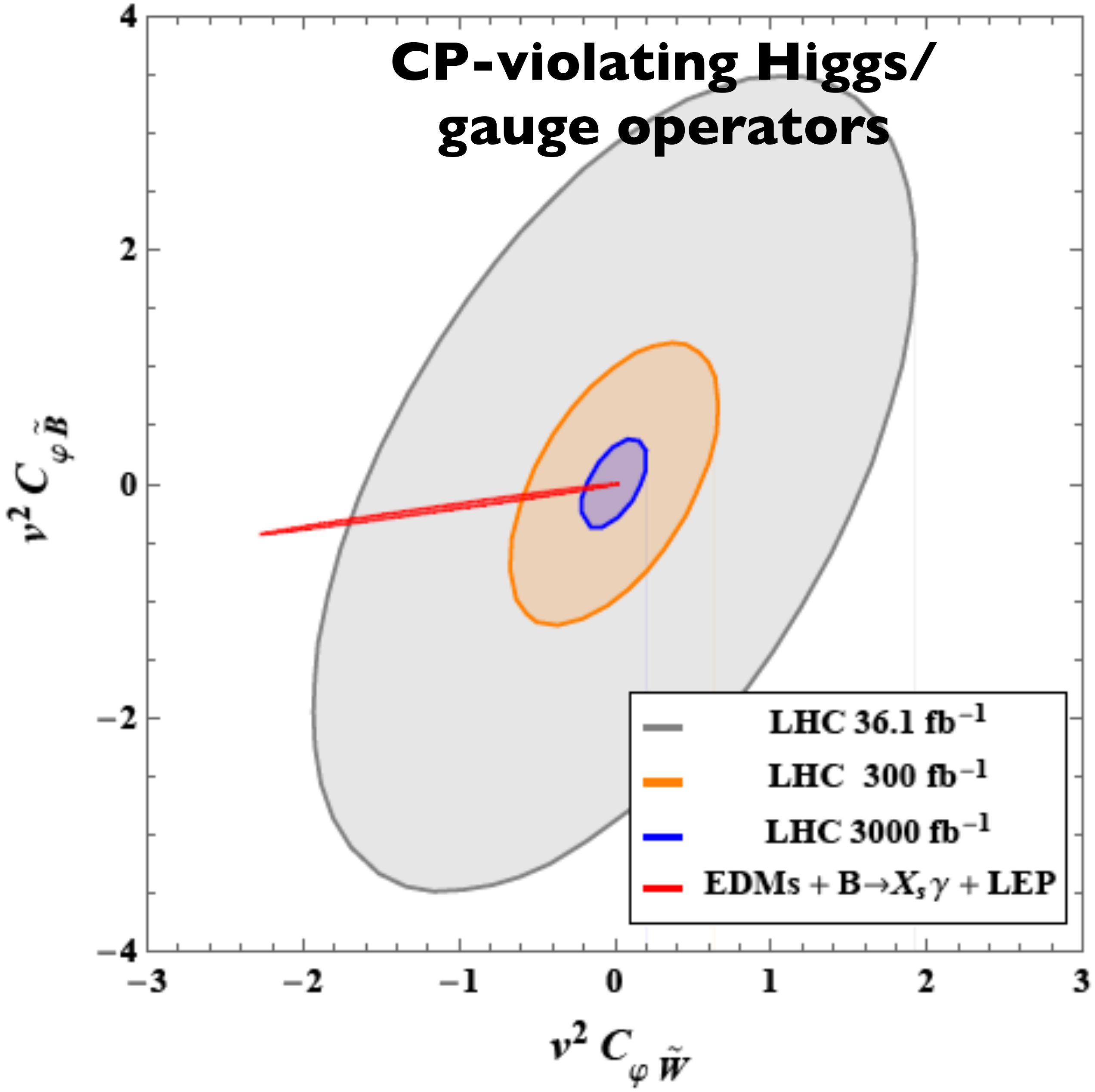
Dimension-6 **Dimension-8**

Higgs vev

$\Lambda \gg$ v, E

Expand in large Λ

Advantages of the SMEFT approach



Cirigliano, Crivellin, Dekens, de Vries, Hoferichter, Mereghetti 1903.03625

$$C_{\phi\tilde{B}} = -g'^2\phi^\dagger\phi\tilde{B}_{\mu\nu}B^{\mu\nu}$$
$$C_{\phi\tilde{W}} = -g^2\phi^\dagger\phi\tilde{W}^I_{\mu\nu}W^{\mu\nu}_I$$

- Convenient language for comparing probes from experiments at disparate energy scales, and understanding the synergies between them.
- **A well-defined QFT**; can systematically improve predictions by including higher-dimension operators, loop corrections

Warsaw basis

- Complete and independent dim-6 basis known: 2499 baryon conserving operators for 3 fermion generations; (can reduce assuming MFV, etc. to O(100)) Grzadkoswki, Iskrzynski, Misiak, Rosiek 1008.4884; Brivio, Jiang, Trott 1709.06492

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

Dim-6 operators

SMEFT cross sections

- Complete and independent dim-6 basis known: 2499 baryon conserving operators for 3 fermion generations; (can reduce assuming MFV, etc. to O(100)) Grzadkoswki, Iskrzynski, Misiak, Rosiek 1008.4884; Brivio, Jiang, Trott 1709.06492

Structure of a SMEFT cross section:

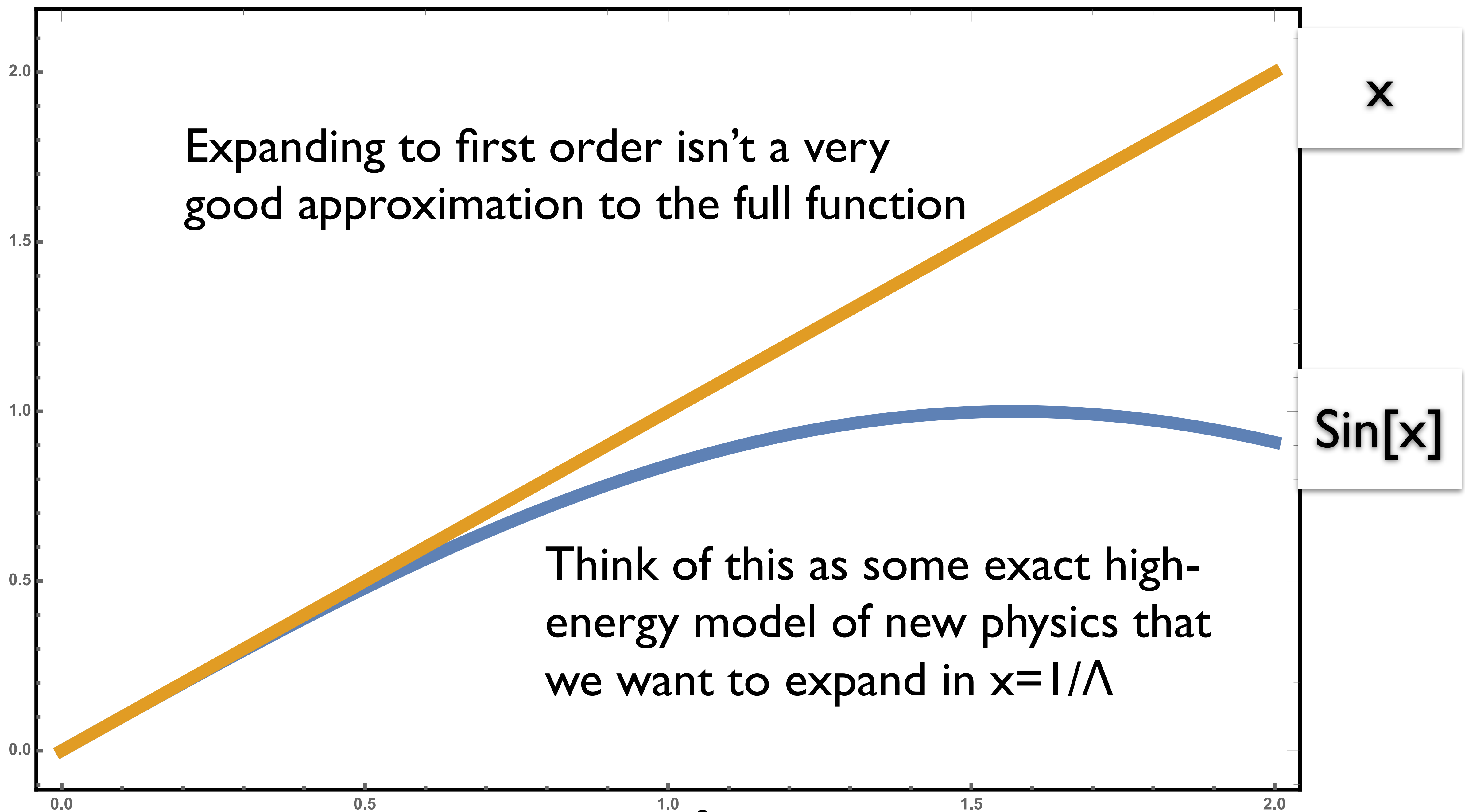
$$\boxed{\sigma \sim |\mathcal{M}_{SM}|^2 + \frac{1}{\Lambda^2} 2\mathrm{Re}\left[\mathcal{M}_6 \mathcal{M}_{SM}^*\right] + \frac{1}{\Lambda^4}\left\{|\mathcal{M}_6|^2 + 2\mathrm{Re}\left[\mathcal{M}_8 \mathcal{M}_{SM}^*\right]\right\}}$$

Leading SMEFT correction

Formally sub-leading in the E/Λ and v/Λ expansions

SMEFT as a series expansion

- Since the SMEFT is a series expansion in 1/Λ, let's recall some facts about series expansions with an elementary example.



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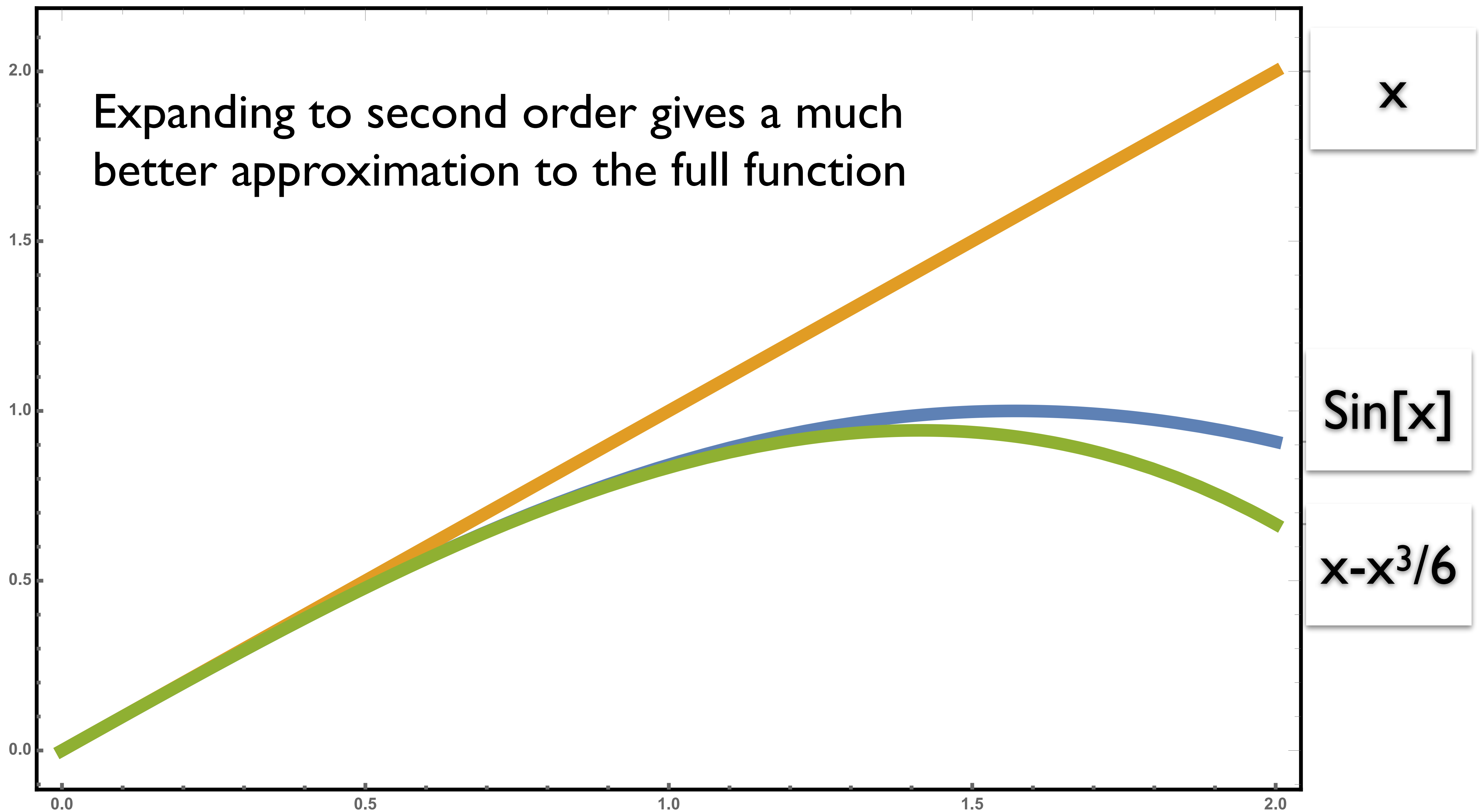

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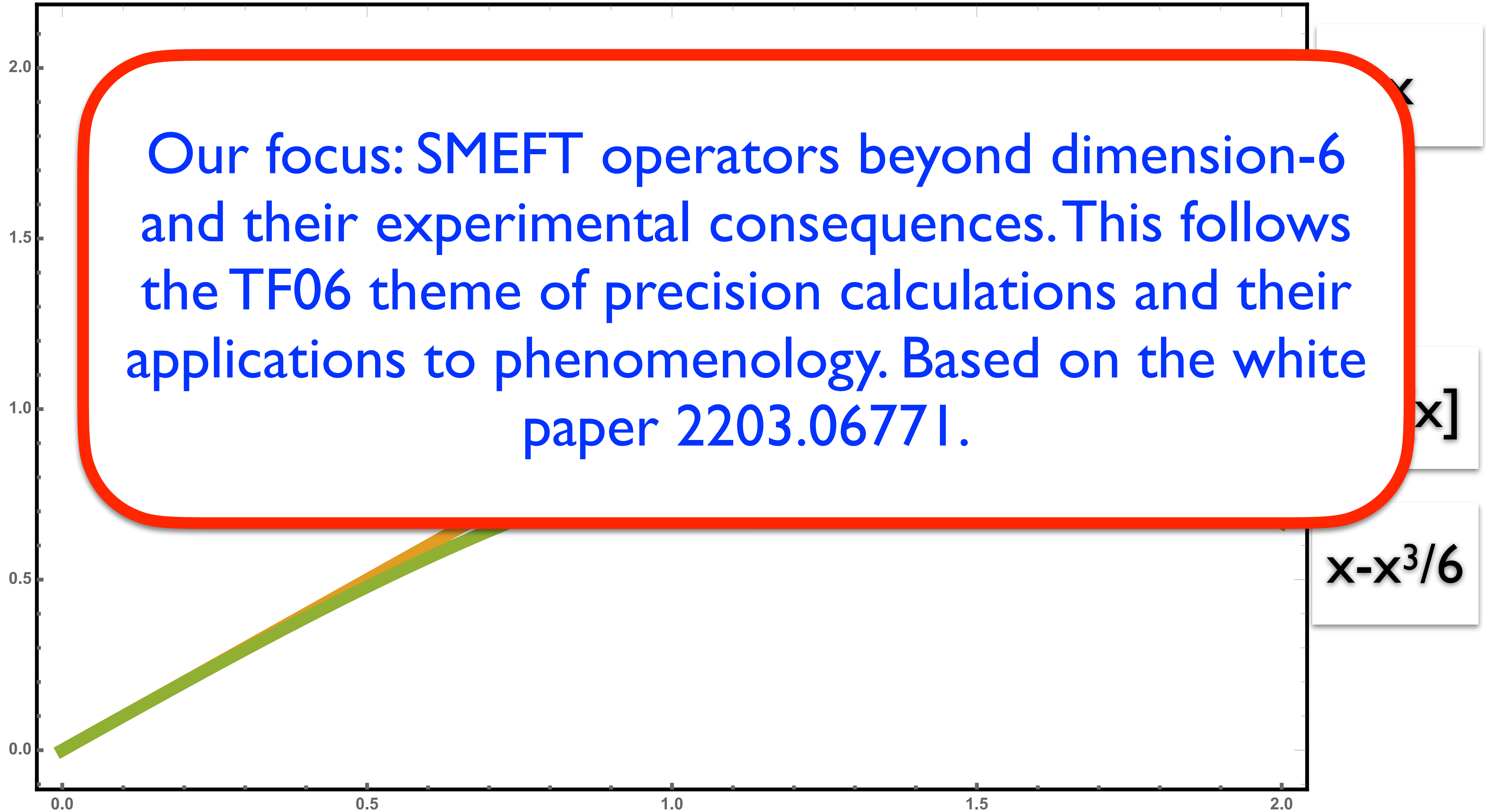

Our focus: SMEFT operators beyond dimension-6 and their experimental consequences. This follows the TF06 theme of precision calculations and their applications to phenomenology. Based on the white paper 2203.06771.

Counting operators

- The first step in this program is to understand the structure of the operator basis at dimension-8 and beyond. The counting of the independent operators that appear at each order was solved by the introduction of *Hilbert series* techniques Lehman, Martin 1503.07537, 1510.00372; Henning, Lu, Melia, Murayama 1512.03433, 1706.08520

$$\boxed{H(\phi,p) = \int \mathrm{d}\mu_{\mathrm{Internal}}(y) \int \mathrm{d}\mu_{\mathrm{Spacetime}}(x)\, \frac{1}{P(p,x)}\, Z(\phi,p,x,y)}$$

Integration over the Lorentz group measure

Integration over the SU(3)xSU(2)xU(1) SM group measure

Factor to remove integration by parts redundancies

Plethystic exponential that encodes information about each particle's group representations

Intuition: Z organizes products of fields according to their charges under each gauge group; the integrations project out the invariant combinations

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$$\boxed{H(\phi,p) = \int d\mu_{\text{Internal}}(y) \int d\mu_{\text{Spacetime}}(x)\, \frac{1}{P(p,x)}\, Z(\phi,p,x,y)}$$

Example output (for baryon number violating operators): Lehman, Martin 1503.07537

$$H = 1 + 57LQ^3 + 4818L^2Q^6 + 162774L^3Q^9 + \ldots$$

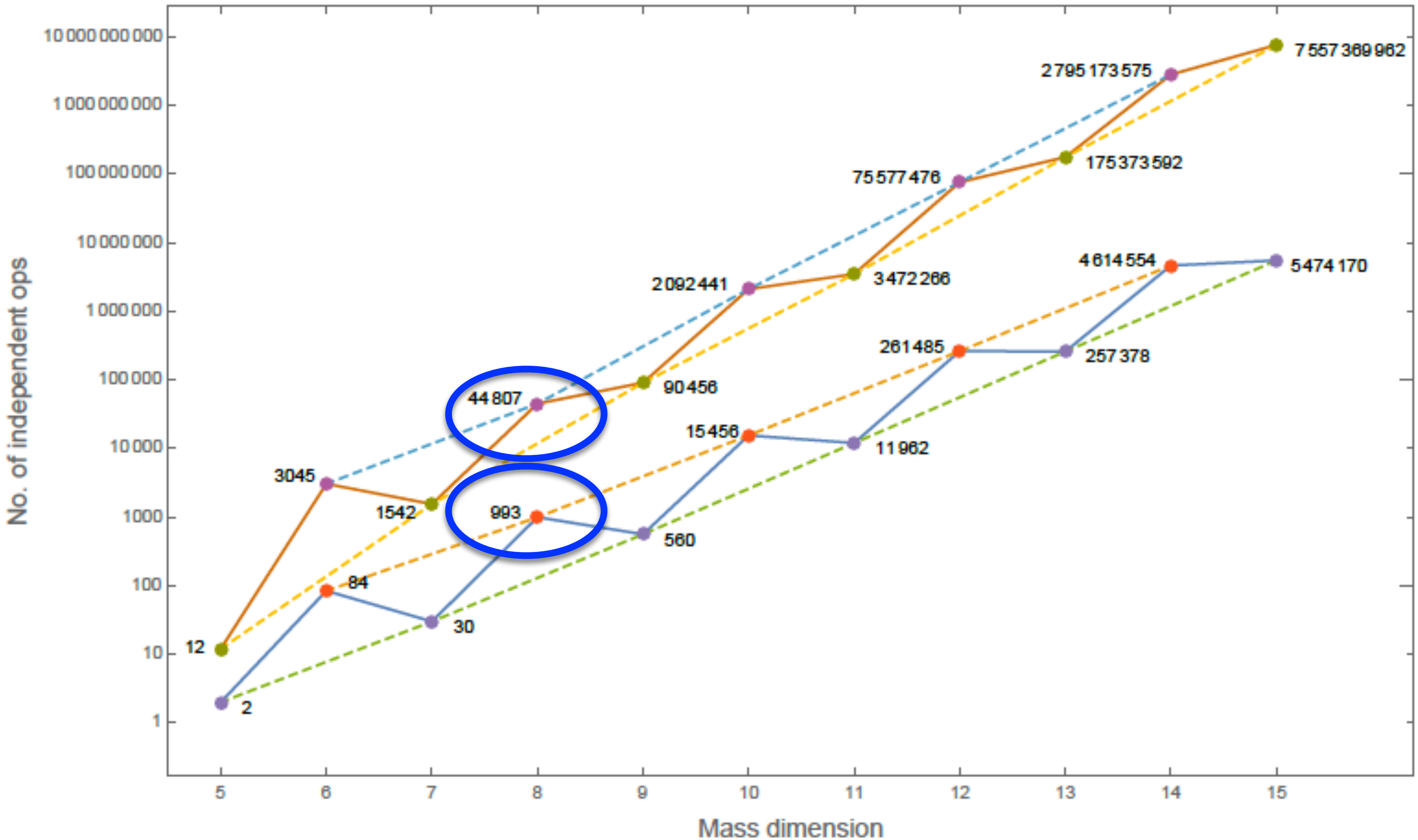
57 dim-6 operators for 3 generations of left-handed lepton doublet L and quark doublets Q

4818 dim-12 operators

162774 dim-16 operators

Counting operators

- 44807 dim-8 operators assuming three generations in the SM; 993 with a single generation Henning, Lu, Melia, Murayama 1512.03433



The operator basis

- The next step in this program is to construct the explicit operator basis, as the Hilbert series only counts the numbers of structures. Historically the first constructions of dim-8 were done by brute force Li et al, 2005.00008, Murphy, 2005.00059; more recently a systematic approach based on Young tensors was developed Li et al, 2007.07899, 2201.04639

$10: \psi^2 X H^3 + \text{h.c.}$	
$Q^{(1)}_{leWH^3}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H (H^\dagger H) W^I_{\mu\nu}$
$Q^{(2)}_{leWH^3}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) H (H^\dagger \tau^I H) W^I_{\mu\nu}$
Q_{leBH^3}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H (H^\dagger H) B_{\mu\nu}$
Q_{quGH^3}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H} (H^\dagger H) G^A_{\mu\nu}$
$Q^{(1)}_{quWH^3}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H} (H^\dagger H) W^I_{\mu\nu}$
$Q^{(2)}_{quWH^3}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H} (H^\dagger \tau^I H) W^I_{\mu\nu}$
Q_{quBH^3}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H} (H^\dagger H) B_{\mu\nu}$
Q_{qdGH^3}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H (H^\dagger H) G^A_{\mu\nu}$
$Q^{(1)}_{qdWH^3}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H (H^\dagger H) W^I_{\mu\nu}$
$Q^{(2)}_{qdWH^3}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) H (H^\dagger \tau^I H) W^I_{\mu\nu}$
Q_{qdBH^3}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H (H^\dagger H) B_{\mu\nu}$

$14: \psi^2 X^2 D$	
$Q^{(1)}_{q^2G^2D}$	$i(\bar{q}_p \gamma^\mu \overleftrightarrow{D}^\nu q_r) G^A_{\mu\rho} G^{A\rho}_\nu$
$Q^{(2)}_{q^2G^2D}$	$i f^{ABC}(\bar{q}_p \gamma^\mu T^A \overleftrightarrow{D}^\nu q_r) G^B_{\mu\rho} G^{C\rho}_\nu$
$Q^{(3)}_{q^2G^2D}$	$i d^{ABC}(\bar{q}_p \gamma^\mu T^A \overleftrightarrow{D}^\nu q_r) G^B_{\mu\rho} G^{C\rho}_\nu$
$Q^{(1)}_{q^2W^2D}$	$i(\bar{q}_p \gamma^\mu \overleftrightarrow{D}^\nu q_r) W^I_{\mu\rho} W^{I\rho}_\nu$
$Q^{(2)}_{q^2W^2D}$	$i \epsilon^{IJK}(\bar{q}_p \gamma^\mu \tau^I \overleftrightarrow{D}^\nu q_r) W^J_{\mu\rho} W^{K\rho}_\nu$
$Q_{q^2B^2D}$	$i(\bar{q}_p \gamma^\mu \overleftrightarrow{D}^\nu q_r) B_{\mu\rho} B^\rho_\nu$
$Q^{(1)}_{u^2G^2D}$	$i(\bar{u}_p \gamma^\mu \overleftrightarrow{D}^\nu u_r) G^A_{\mu\rho} G^{A\rho}_\nu$
$Q^{(2)}_{u^2G^2D}$	$i f^{ABC}(\bar{u}_p \gamma^\mu T^A \overleftrightarrow{D}^\nu u_r) G^B_{\mu\rho} G^{C\rho}_\nu$
$Q^{(3)}_{u^2G^2D}$	$i d^{ABC}(\bar{u}_p \gamma^\mu T^A \overleftrightarrow{D}^\nu u_r) G^B_{\mu\rho} G^{C\rho}_\nu$
$Q_{u^2W^2D}$	$i(\bar{u}_p \gamma^\mu \overleftrightarrow{D}^\nu u_r) W^I_{\mu\rho} W^{I\rho}_\nu$
$Q_{u^2B^2D}$	$i(\bar{u}_p \gamma^\mu \overleftrightarrow{D}^\nu u_r) B_{\mu\rho} B^\rho_\nu$
$Q^{(1)}_{d^2G^2D}$	$i(\bar{d}_p \gamma^\mu \overleftrightarrow{D}^\nu d_r) G^A_{\mu\rho} G^{A\rho}_\nu$
$Q^{(2)}_{d^2G^2D}$	$i f^{ABC}(\bar{d}_p \gamma^\mu T^A \overleftrightarrow{D}^\nu d_r) G^B_{\mu\rho} G^{C\rho}_\nu$
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$Q_{d^2W^2D}$	$i(\bar{d}_p \gamma^\mu \overleftrightarrow{D}^\nu d_r) W^I_{\mu\rho} W^{I\rho}_\nu$
$Q_{d^2B^2D}$	$i(\bar{d}_p \gamma^\mu \overleftrightarrow{D}^\nu d_r) B_{\mu\rho} B^\rho_\nu$

$18: (\bar{L}L)(\bar{L}L)H^2$	
$Q^{(1)}_{l^4H^2}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu l_t)(H^\dagger H)$
$Q^{(2)}_{l^4H^2}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu \tau^I l_t)(H^\dagger \tau^I H)$
$Q^{(1)}_{q^4H^2}$	$(\bar{q}_p \gamma^\mu q_r)(\bar{q}_s \gamma_\mu q_t)(H^\dagger H)$
$Q^{(2)}_{q^4H^2}$	$(\bar{q}_p \gamma^\mu q_r)(\bar{q}_s \gamma_\mu \tau^I q_t)(H^\dagger \tau^I H)$
$Q^{(3)}_{q^4H^2}$	$(\bar{q}_p \gamma^\mu \tau^I q_r)(\bar{q}_s \gamma_\mu \tau^I q_t)(H^\dagger H)$
$Q^{(1)}_{l^2q^2H^2}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)(H^\dagger H)$
$Q^{(2)}_{l^2q^2H^2}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu q_t)(H^\dagger \tau^I H)$
$Q^{(3)}_{l^2q^2H^2}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)(H^\dagger H)$
$Q^{(4)}_{l^2q^2H^2}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)(H^\dagger \tau^I H)$
$Q^{(5)}_{l^2q^2H^2}$	$\epsilon^{IJK}(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^J q_t)(H^\dagger \tau^K H)$

General constraints on Wilson coefficients

- The Wilson coefficients multiplying each of these operators in the SMEFT are arbitrary; however, at dimension-8 we can use the general principles of unitarity and analyticity of the underlying UV theory to constrain this parameter space
  Zhang, Zhou 2005.03047; Li et al 2101.01191

Simplest *positivity bound* for the forward-scattering limit of the process ij→ij:

$$\boxed{\frac{1}{2}\frac{d^2 M_{ijij}(0)}{ds^2} \geq 0}$$

Two derivatives means it probes dim-8 coefficients; dim-6 amplitudes grow as s/Λ^2, while dim-8 grows as s^2/Λ^4

Drell-Yan example:
Li et al 2204.13121

Positivity bound
$-4C_{8,lq\partial 3} + 4C_{8,lq\partial 4} \geq 0$
$-4C_{8,lq\partial 3} - 4C_{8,lq\partial 4} \geq 0$
$-4C_{8,ed\partial 2} \geq 0$
$-4C_{8,eu\partial 2} \geq 0$
$-4C_{8,ld\partial 2} \geq 0$
$-4C_{8,lu\partial 2} \geq 0$
$-4C_{8,qe\partial 2} \geq 0$

$$O_{8,lq\partial 3} = (\bar{\ell}\gamma_\mu \overleftrightarrow{D}_\nu \ell)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q)$$
$$O_{8,lq\partial 4} = (\bar{\ell}\tau^I\gamma_\mu \overleftrightarrow{D}_\nu \ell)(\bar{q}\tau^I\gamma^\mu \overleftrightarrow{D}^\nu q)$$
$$O_{8,ed\partial 2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d)$$
$$O_{8,eu\partial 2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u)$$
$$O_{8,ld\partial 2} = (\bar{\ell}\gamma_\mu \overleftrightarrow{D}_\nu \ell)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d)$$
$$O_{8,lu\partial 2} = (\bar{\ell}\gamma_\mu \overleftrightarrow{D}_\nu \ell)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u)$$
$$O_{8,qe\partial 2} = (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q)$$

RG running and positivity bounds

- The interplay of renormalization group running and these constraints is being studied. In general these bounds are not scale-invariant; if imposed at the renormalization scale μ=Λ, they may not hold at other scales Chala, Santiago 2110.01624

$$\mathcal{O}^{(1)}_{H^4} = (D_\mu H^\dagger D_\nu H^\dagger)(D^\nu H^\dagger D^\mu H^\dagger)$$
$$\mathcal{O}^{(2)}_{H^4} = (D_\mu H^\dagger D_\nu H^\dagger)(D^\mu H^\dagger D^\nu H^\dagger)$$
$$\mathcal{O}^{(2)}_{H^4} = (D_\mu H^\dagger D^\mu H^\dagger)(D_\nu H^\dagger D^\nu H^\dagger)$$

Positivity →

$$C^{(2)}_{H^4} \geq 0$$
$$C^{(1)}_{H^4} + C^{(2)}_{H^4} \geq 0$$
$$C^{(1)}_{H^4} + C^{(2)}_{H^4} + C^{(3)}_{H^4} \geq 0$$

We can satisfy this bound at μ=Λ with $C^{(1)}(\Lambda)=0$, $C^{(2)}(\Lambda)$,$C^{(3}(\Lambda)>0$.

RG running →

$C^{(2)}(\mu)$ can be negative

$$\boxed{c^{(2)}_{H^4}(\mu) = \frac{1}{96\pi^2}\left[28c^{(1)}_{H^4}(\Lambda) + 15c^{(3)}_{H^4}(\Lambda)\right] g_2^2 \log\frac{\mu}{\Lambda} + \mathcal{O}(g_1^2, \lambda)}$$

RG running and positivity bounds

- The interplay of renormalization group running and these constraints is being studied. In general these bounds are not scale-invariant; if imposed at the renormalization scale $\mu=\Lambda$, they may not hold at other scales Chala, Santiago 2110.01624

Different conclusions hold for other operators; for example, positivity bounds on $X^2\Phi^2D^2$ hold at all scales at 1-loop order Bakshi, Chala, Diaz-Carmona, Guedes 2205.03301. Recent work extends similar dispersive bounds to to dim-6, where the details of the UV theory matter Remmen, Rodd 2206.13524. More exploration needed!

Phenomenology: new effects at dim-8

- We can now discuss the phenomenology that appears at the dimension-8 level. Qualitatively new effects can appear at this order which are ripe for LHC exploration.

$$\begin{aligned}
\mathcal{O}_{8,ed\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d), \\
\mathcal{O}_{8,eu\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u), \\
\mathcal{O}_{8,ld\partial 2} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{d}\gamma^\mu \overleftrightarrow{D}^\nu d), \\
\mathcal{O}_{8,lu\partial 2} &= (\bar{l}\gamma_\mu \overleftrightarrow{D}_\nu l)(\bar{u}\gamma^\mu \overleftrightarrow{D}^\nu u), \\
\mathcal{O}_{8,qe\partial 2} &= (\bar{e}\gamma_\mu \overleftrightarrow{D}_\nu e)(\bar{q}\gamma^\mu \overleftrightarrow{D}^\nu q).
\end{aligned}$$

$$\begin{aligned}
\frac{d\sigma}{dm_{ll}^2\,dy\,d\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dm_{ll}^2\,dy}\Big\{&(1+c_\theta^2) + \frac{A_0}{2}(1-3c_\theta^2) \\
&+A_1 s_{2\theta}c_\phi + \frac{A_2}{2}s_\theta^2 c_{2\phi} + A_3 s_\theta c_\phi + A_4 c_\theta \\
&+A_5 s_\theta^2 s_{2\phi} + A_6 s_{2\theta}s_\phi + A_7 s_\theta s_\phi \\
&\boxed{\begin{aligned}&+B_3^e s_\theta^3 c_\phi + B_3^o s_\theta^3 s_\phi + B_2^e s_\theta^2 c_\theta c_{2\phi} \\
&+B_2^o s_\theta^2 c_\theta s_{2\phi} + \frac{B_1^e}{2}s_\theta(5c_\theta^2-1)c_\phi \\
&+\frac{B_1^o}{2}s_\theta(5c_\theta^2-1)s_\phi + \frac{B_0}{2}(5c_\theta^3-3c_\theta)\Big\}\end{aligned}}.
\end{aligned}$$

New l=3 spherical harmonics in the angular distribution of the Drell-Yan process first appear at the dimension-8 level Alioli, Boughezal, Mereghetti, FP 2003.11615

Phenomenology: new effects at dim-8

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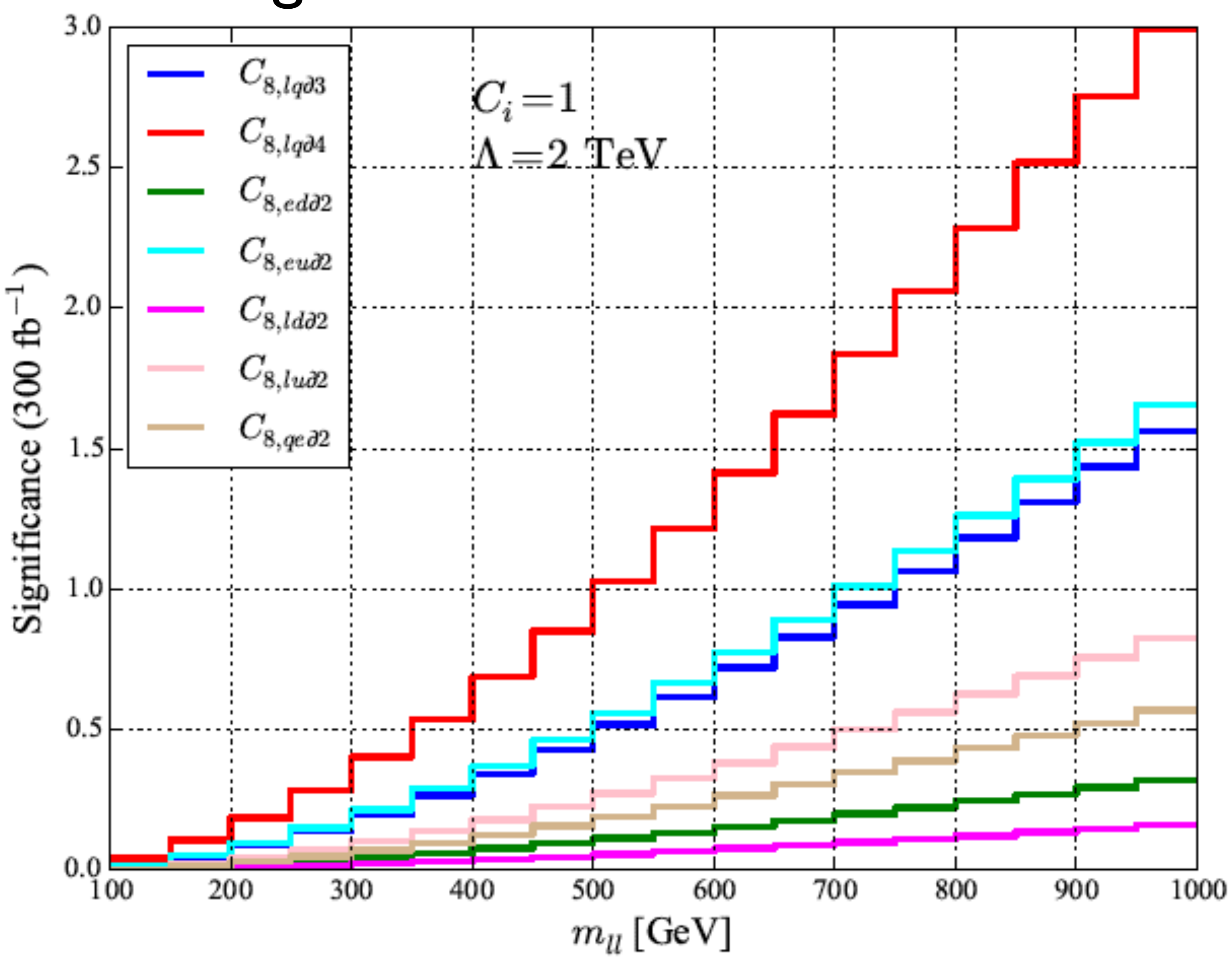
Significant for B_0 coefficient



Alioli, Boughezal, Mereghetti, FP 2003.11615

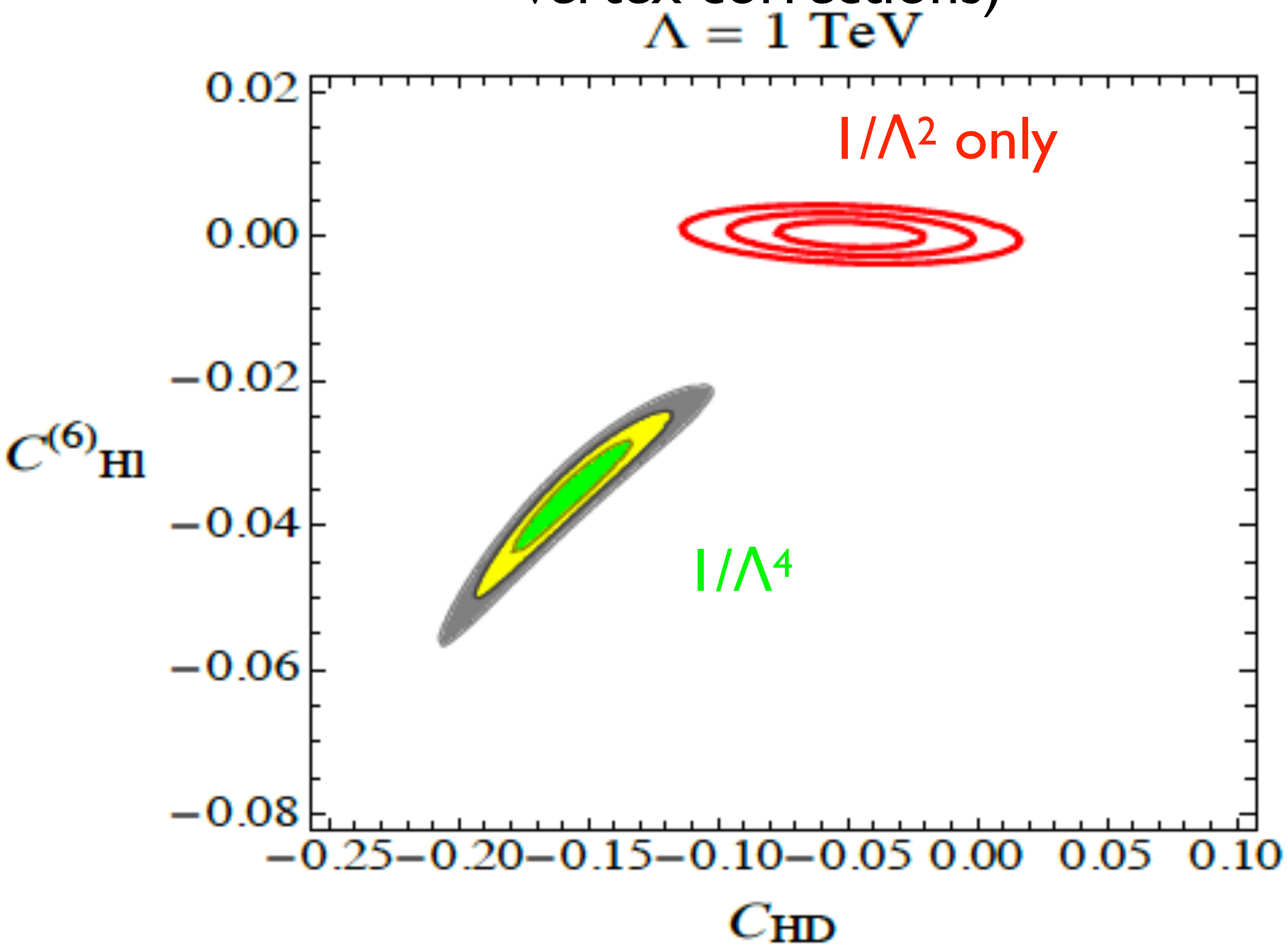
- Single-bin significance reaches 3 for largest operator with 300 fb^{-1}
- Combining 600-1000 GeV bins leads to Sig>6 for largest operator, Sig>3.5 for next two
- HL-LHC increases these results by $\sqrt{10}$

Promising "smoking gun" signature of dim-8 at the LHC

Phenomenology: impact on dim-6 bounds

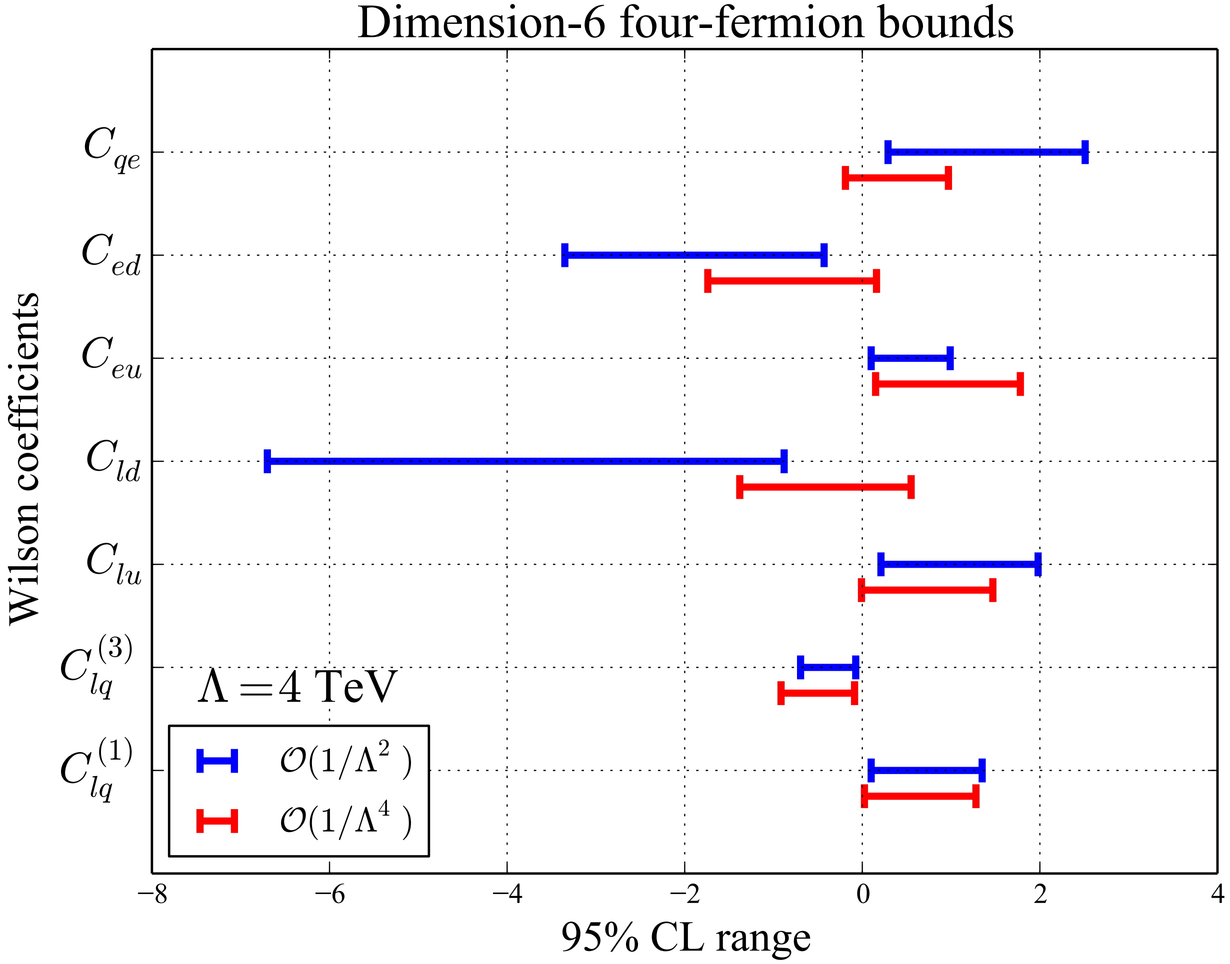
- Extending fits to data to include $1/\Lambda^4$ dimension-6 squared effects can have a significant impact on the constraints.

fit to EW precision data (Zff vertex corrections)



Corbett, Helset, Martin, Trott 2102.02819

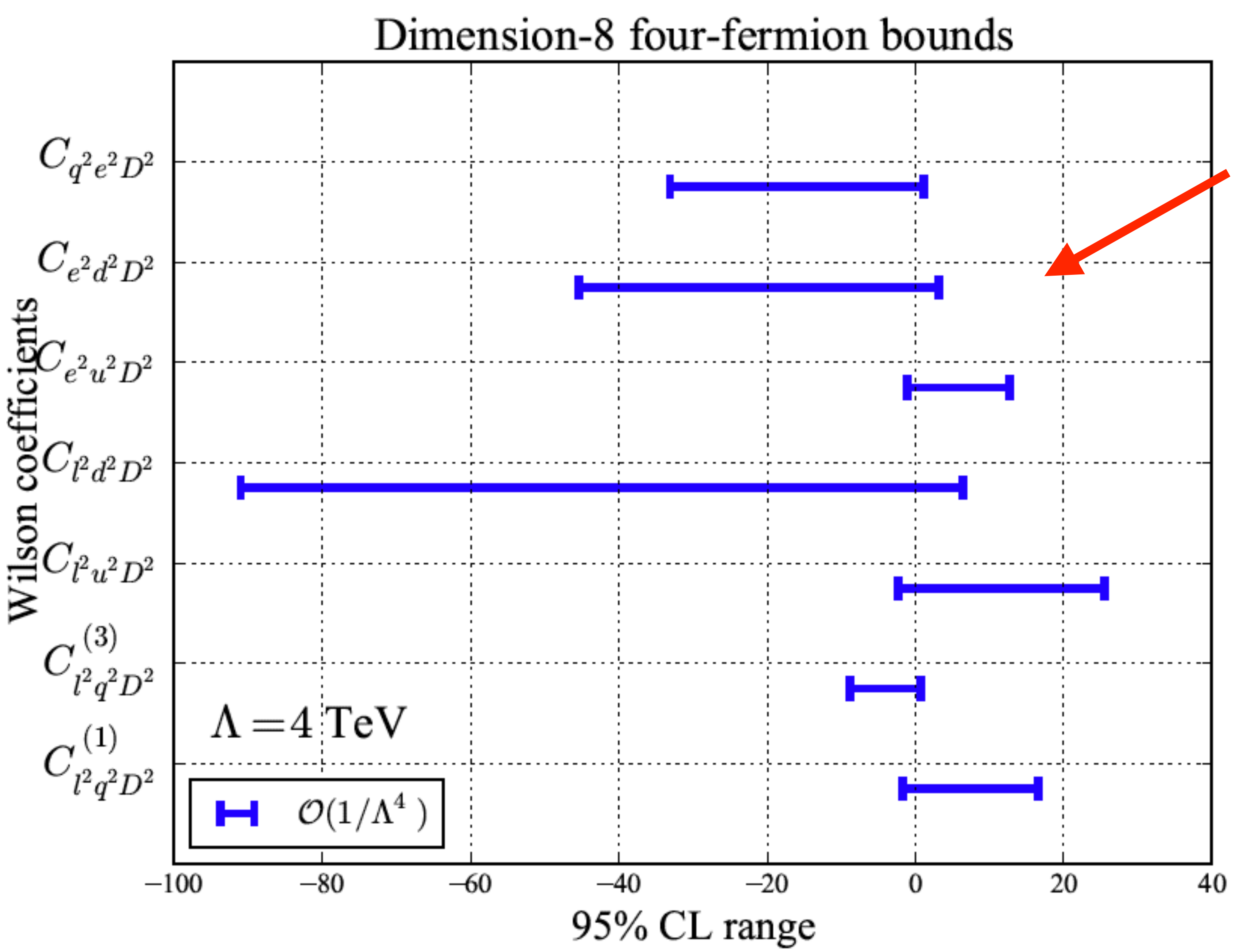
fit to ATLAS DY data (four-fermion operators)



Boughezal, Mereghetti, FP 2106.05337

Phenomenology: probes of dim-8 operators

- LHC 8 TeV data can already probe dim-8 operators at the TeV level! Going forward all $1/\Lambda^4$ effects should be included in fits to LHC data.



$$\frac{C^{(1)}_{l^2q^2D^2}}{\Lambda^4}\partial_\nu(\bar{l}\gamma^\mu l)\partial^\nu(\bar{q}\gamma_\mu q)$$

$$\frac{C^{(1)}_{l^2d^2D^2}}{\Lambda^4}\partial_\nu(\bar{l}\gamma^\mu l)\partial^\nu(\bar{d}\gamma_\mu d)$$

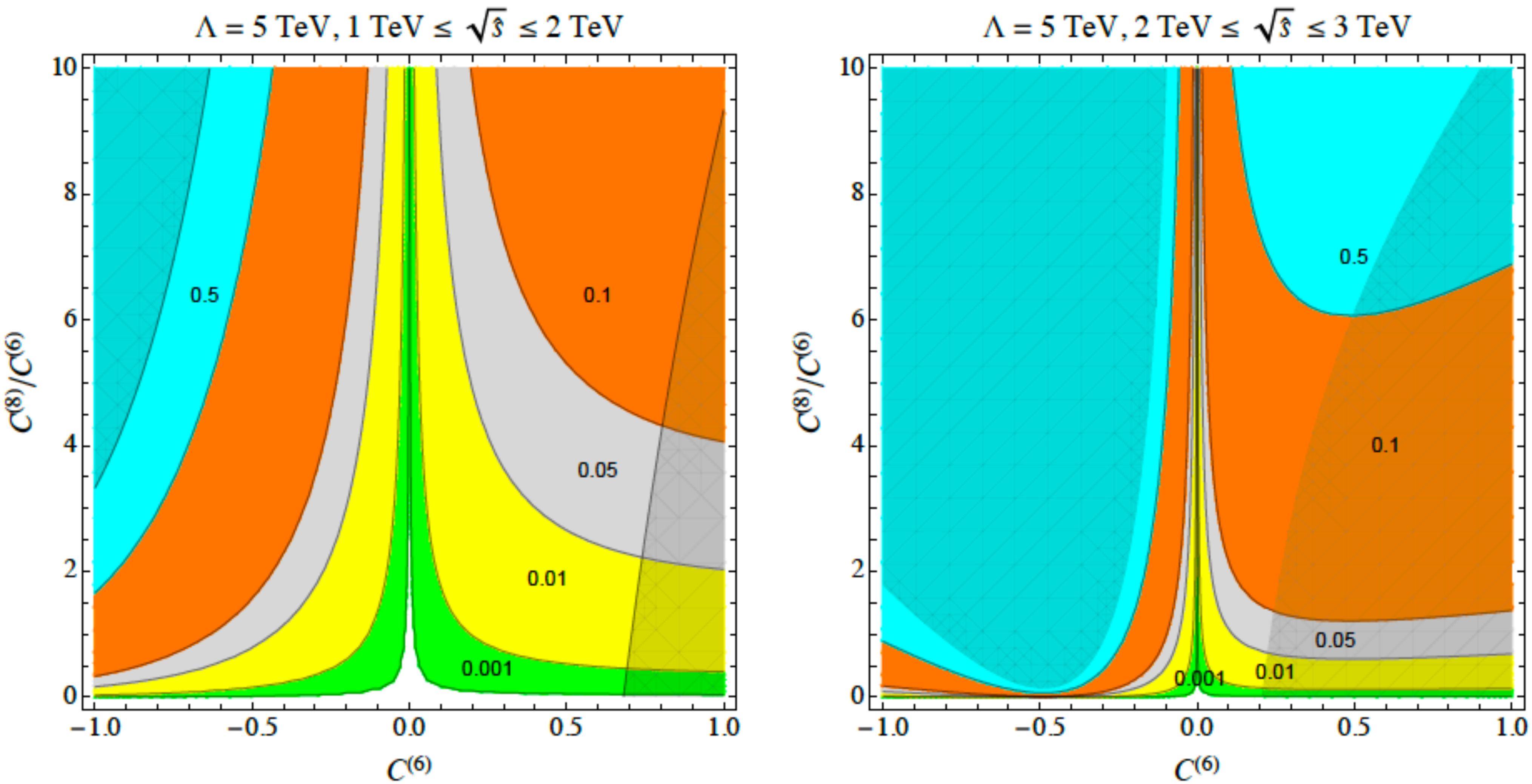
- $\Lambda_{eff}=\Lambda/\sqrt[4]{C}$
- Effective scales probed reach multi-TeV for several operators
- $O(s^2/\Lambda^4)$ scaling makes these effects sizable

Boughezal, Mereghetti, FP 2106.05337

Phenomenology: probes of dim-8 operators

- More unrealized opportunities exist to study the SMEFT beyond dim-6 at the LHC, for example in charged current lepton production.

pp→lν at 13 TeV



- Dim-8 can reach 50% or more of dim-6 effects in regions accessible with LHC measurements

Kim, Martin 2203.11976

Phenomenology: diagnosing UV models with dim-8

- The pattern of dim-8 coefficients can help point toward the underlying UV model giving rise to new physics. Consider an example focusing on deviations in the Drell-Yan process.

$$\boxed{\begin{aligned} &\text{Dim-6:}\ \mathcal{O}_{eu} = (\bar{e}\gamma^{\mu}e)(\bar{u}\gamma_{\mu}u) \\ &\text{Dim-8:}\ \mathcal{O}_{e^2u^2D^2} = D_{\nu}(\bar{e}\gamma^{\mu}e)D^{\nu}(\bar{u}\gamma_{\mu}u) \\ &\qquad\quad\ \mathcal{O}_{e^2u^2\tilde{G}} = (\bar{e}\gamma^{\mu}e)(\bar{u}\gamma^{\nu}T^{A}u)\tilde{G}^{A}_{\mu\nu} \end{aligned}}$$

Can be probed by LHC transverse momentum measurements

Right-handed Z′:

$$C_{eu}/\Lambda^2 = -g^2_{Z'}g^e_R g^u_R/M^2_{Z'}$$
$$C_{e^2u^2D^2}/\Lambda^4 = -g^2_{Z'}g^e_R g^u_R/M^4_{Z'}$$
$$C_{e^2u^2\tilde{G}}/\Lambda^4 = 0$$

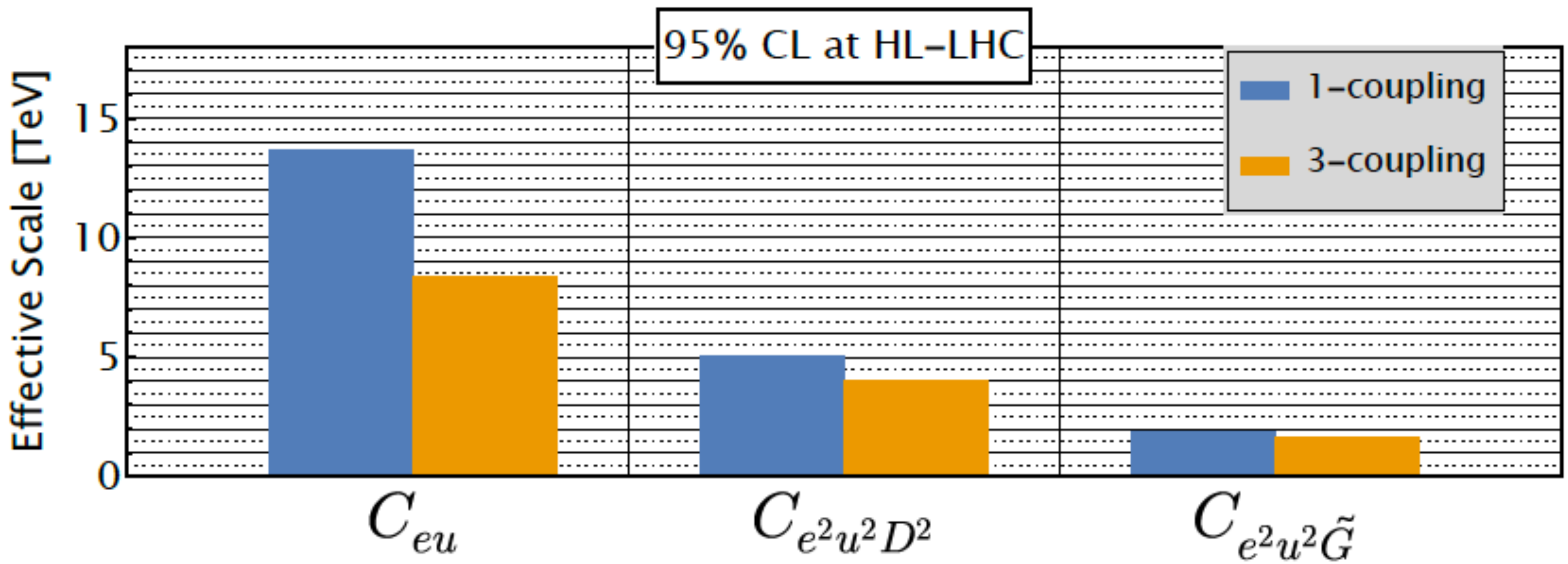
Vector leptoquark:

$$C_{eu}/\Lambda^2 = h^2_U/M^2_U$$
$$C_{e^2u^2D^2}/\Lambda^4 = -h^2_U/(4M^4_U)$$
$$C_{e^2u^2\tilde{G}}/\Lambda^4 = -g_s h^2_U(1-\kappa_U)/(2M^4_U)$$

Boughezal, Huang, FP 2207.01703

Phenomenology: diagnosing UV models with dim-8

- The pattern of dim-8 coefficients can help point toward the underlying UV model giving rise to new physics. Consider an example focusing on deviations in the Drell-Yan process.



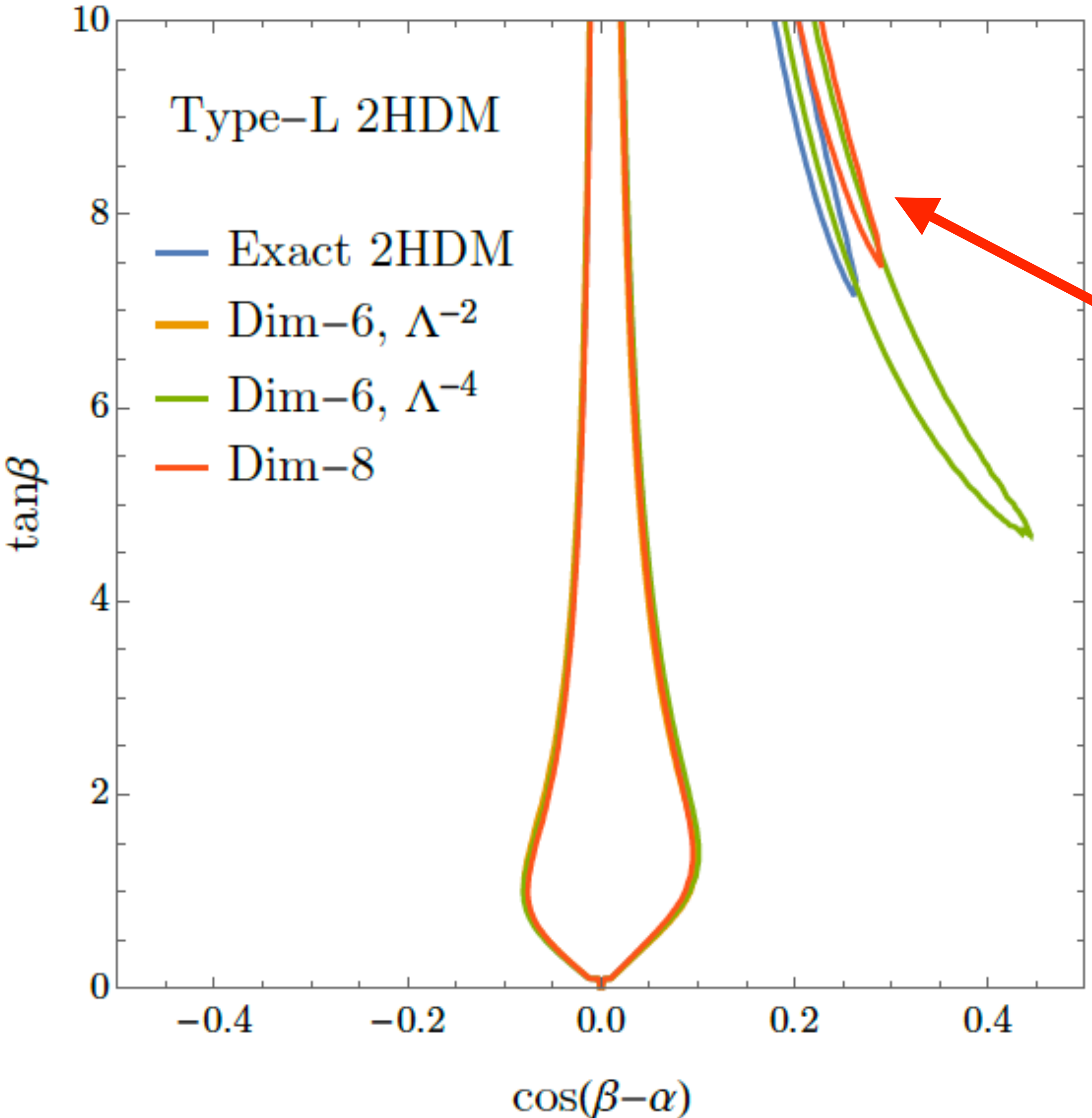
It is important to probe the full spectrum of operators at the HL-LHC!

Boughezal, Huang, FP 2207.01703

Phenomenology: reproducing UV models with dim-8

- The inclusion of dim-8 effects is sometimes crucial in faithfully reproducing the underlying UV model, like in this 2HDM example.

95% CL bounds from LHC



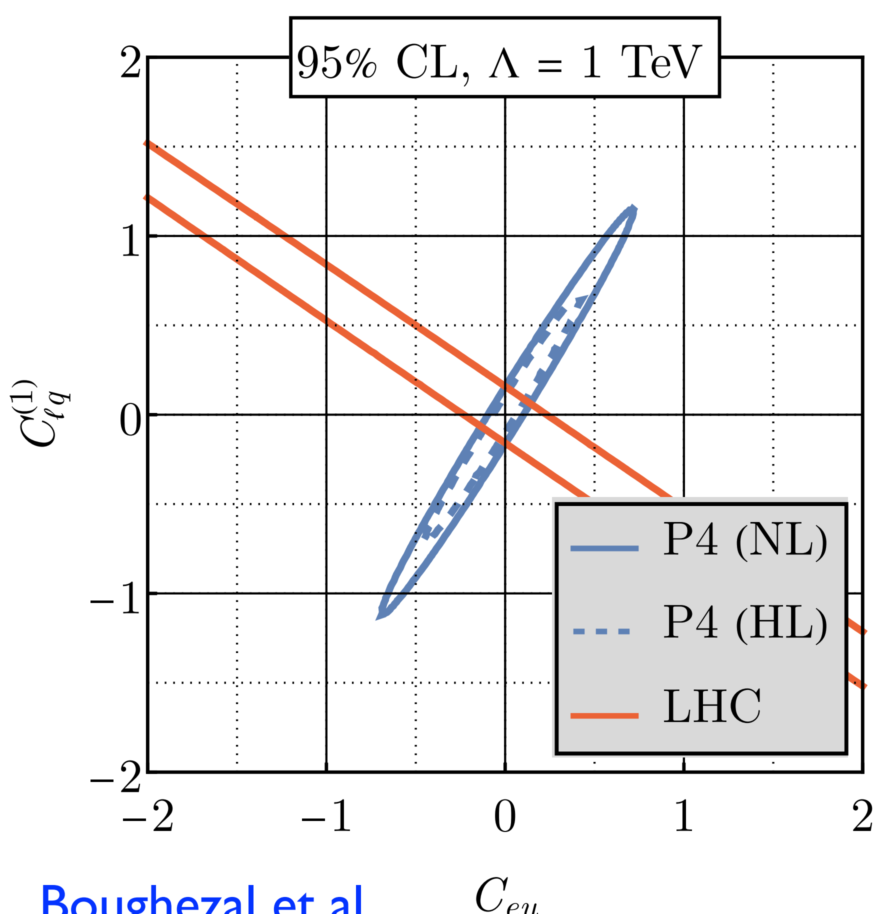
Only capture the correct qualitative behavior in the SMEFT upon including $1/\Lambda^4$ effects; only get the correct quantitative result upon including genuine dim-8

Dawson, Fontes, Homiller, Sullivan 2205.01561

Phenomenology: synergies with other fields

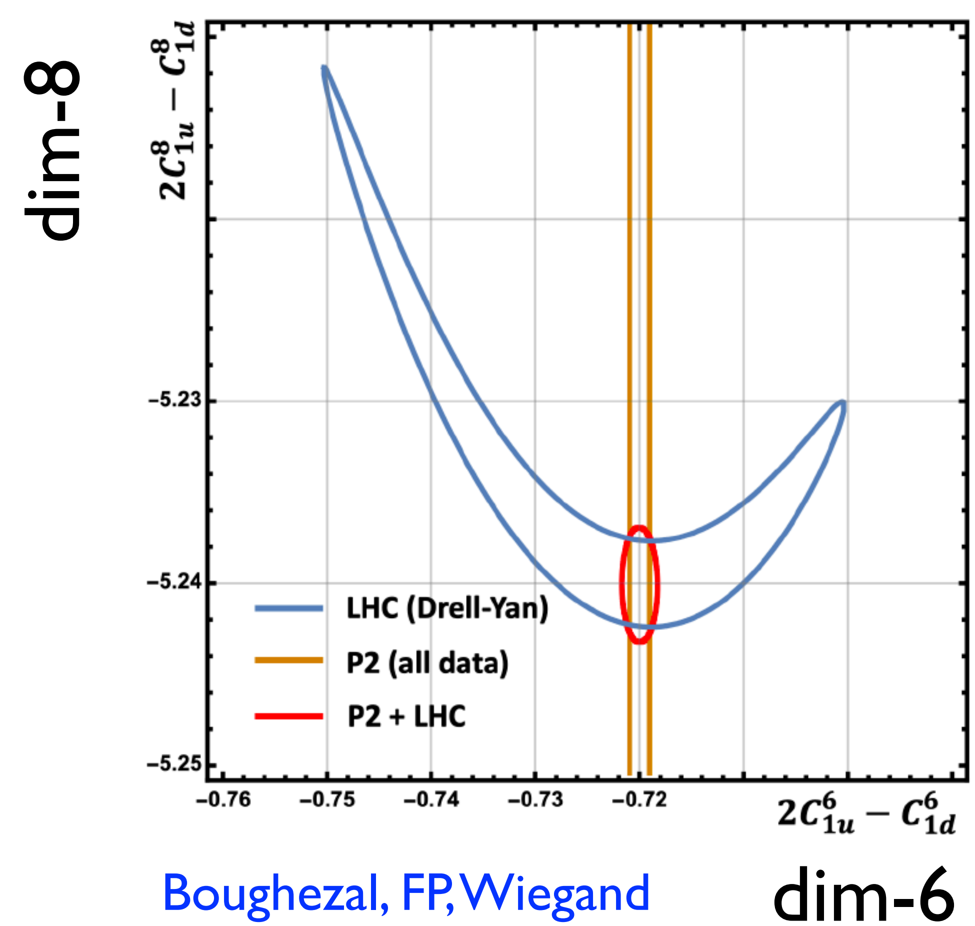
- Fully probing the large parameter space of the SMEFT will require a rich spectrum of experiments, both high-energy ones such as the LHC as well as lower-energy experiments.

future Electron-Ion Collider polarized DIS data can remove blind spots in LHC semi-leptonic four-fermion operator coverage



Boughezal et al
2004.00748, .2204.07557

low-energy PVES data from the P2 experiment can help disentangle dim-6, dim-8



Boughezal, FP, Wiegand
2104.03979

Conclusions

- The extension of the SMEFT to the dimension-8 level has received significant attention in the past few years, including the construction of the complete operator basis.
- Important studies remain to be done including what can be said in general about the Wilson coefficients from general principles of QFT, and how faithfully the SMEFT reproduces UV models.
- Novel phenomenology at the LHC in numerous channels, only starting to be explored. Dimension-8 effects should not be neglected in current fits to LHC data; they have a significant impact!
- Important input will be required from experiments in other fields, ranging from low-energy to the EIC.